

Implications Of A Dark Sector $U(1)$ For Gamma Ray Bursts

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We discuss the implications for gamma ray burst studies, of a dark unbroken $U(1)_D$ sector that couples predominantly through gravity to the visible sector. The dominant dark matter component remains neutral under $U(1)_D$. The collapsar model is assumed to explain the origin of long gamma ray bursts. The main idea is that by measuring the change in stellar black hole spin during the duration of the GRB, one can make inferences about the existence of a dark matter accretion disk. This could potentially provide evidence for the existence for a $U(1)_D$ sector.

INTRODUCTION

The possible existence of a dark unbroken $U(1)_D$ sector, complete with dark photons, charged particles, and perhaps even dark Hydrogen has been extensively considered in the literature [1–15]. For simplicity, we will consider dark matter that is neutral under the standard model. The dominant dark matter component is neutral under the $U(1)_D$ sector. We will assume there is some excess of dark charged particles such that neutral Hydrogen may be formed as in the visible sector. In this type of scenario, dark matter may form more complicated astrophysical structure such as galactic disks [11–13, 15]. Astrophysical observations such as halo shape analysis [16–18] and the bullet cluster [19–23] will bound the amount of allowed charged dark matter, but ultimately cannot provide evidence for its existence.

We will assume that the collapsar model [24–26], whereby the iron core of a progenitor star collapses into a black hole, describes some of the observed long gamma ray bursts and is followed by jet emission which is powered by the Blandford-Znajek (BZ) mechanism [27–40]. We observe these jets as gamma ray bursts [36]. While there are competing theories about the origin of jets, numerical studies indicate that it is more likely that astrophysical jets are the result of the BZ mechanism rather than the Penrose mechanism or accretion disk braking [34, 36, 38], for at least some sets of parameters.

If a $U(1)_D$ sector exists, it will accrete around a black hole and emit jets of dark radiation that are unobservable by visible sector photodetectors. The mechanism underlying both the dark jet production and the visible jet production is identical. Therefore the black hole rotational energy will decrease more rapidly than expected from the case of visible jets alone. We derive an equation

for the amount of $U(1)_D$ energy density in the vicinity of the newly formed black hole. We expect the visible sector and dark sector accretion disks to be formed in a similar manner since they are subject to the same gravitational environment. This will need to be checked with “two-sector” numerical simulations. We also note that the bounds we derive are easily evaded. If the $U(1)_D$ charged dark matter is too massive or the dark fine structure constant too small the effect disappears.

TEMPORAL CHANGE IN BLACK HOLE SPIN

The rotational energy of a Kerr black hole is given by subtracting the irreducible mass contribution from the total energy [41]

$$E_{rot} = \frac{M_B}{2} \left\{ 2 - \left[\left(1 + \sqrt{1 - a^2} \right)^2 + a^2 \right]^{1/2} \right\}, \quad (1)$$

where $a = J/G M_B^2$ is the dimensionless spin parameter. Defining $\gamma \equiv \left(1 - \frac{E_{rot}}{M_B} \right)$ and solving (1) for the spin parameter yields

$$a = 2\gamma (1 - \gamma^2)^{1/2}. \quad (2)$$

The value of the spin parameter has recently been measured for several stellar mass black holes [42]. Our proposal is to constrain the $U(1)_D$ energy density by measuring both the temporal change in stellar black hole spin and the energy emitted in jets during a gamma ray burst event. Defining $\lambda \equiv -2 \frac{(1 - 2\gamma^2)}{(1 - \gamma^2)^{1/2}} = 2\sqrt{2} \left(\frac{1 - a^2}{1 - \sqrt{1 - a^2}} \right)^{1/2}$, the derivative of the spin parameter with respect to time may

be shown to be

$$\dot{a} = 2\dot{\gamma} \frac{(1 - 2\gamma^2)}{(1 - \gamma^2)^{1/2}} \equiv -\lambda\dot{\gamma} \quad (3)$$

There are two contributions to $\dot{\gamma}$, one proportional to the change in rotational energy and the other proportional to the mass accretion rate

$$\dot{\gamma} = \frac{\dot{E}_{rot}}{M_B} - \frac{E_{rot}}{M_B} \frac{\dot{M}_B}{M_B}. \quad (4)$$

For the entirety of this study, we are interested in the time regime after an accretion disk has been formed so that accretion rate is a meaningful concept. In order to assess the relative contribution of each term contributing to $\dot{\gamma}$, it is first necessary to estimate the size of \dot{E}_{rot} .

Within the assumptions outlined in the introduction, the three contributions to the \dot{E}_{rot} are accretion, jet emission, and the emission of gravitational radiation

$$\frac{\dot{E}_{rot}}{M_B} = \frac{\dot{E}_{acc}}{M_B} - \frac{\dot{E}_{BZ}}{M_B} - \frac{\dot{E}_{gr}}{M_B} \approx -\frac{\dot{E}_{BZ}}{M_B}. \quad (5)$$

There may be other sources of rotational energy loss that we are neglecting here which may be quantified with numerical simulations, but we will restrict our attention to these three contributions. Compared to the typical value of BZ emitted power [34] $\frac{\dot{E}_{BZ}}{M_B} \approx 10^{-4}/s$, the gravitational radiation emission [43] $\frac{\dot{E}_{gr}}{M_B} \lesssim 10^{-9}/s$ is negligible. Note that the temporal change in rotational energy due to mass accretion during the accretion disk regime is model dependent and needs to be checked with numerical simulations for the type of scenario we propose. Existing numerical simulations show the development of plateaus to a slow rate after the formation of the accretion disk (see figure 19 of [26]).

We will now show that the second term in (4) is negligible compared to the first term for some set of parameters. The quantity $\frac{\dot{E}_{rot}}{M_B}$ must be less than one since the dimensionless spin parameter a , and hence γ , must be less than one. Additionally, it has been found numerically that situations exist whereby the power accreted is less than the power emitted [39], $\dot{E}_{BZ} > \dot{M}_B$. Therefore there exists a region in parameter space whereby $\dot{\gamma} \approx \dot{E}_{BZ}$. Since the visible $U(1)$ sector and the dark $U(1)$ sector are subject to the same gravitational environment, we will assume that both will emit jets at approximately the same time. This may imply that the combinations of electron mass and fine structure constant, which appear in the BZ equations, are approximately the same for visible and dark $U(1)$ sectors. The temporal change in black hole spin may therefore be written as

$$\dot{a} \approx -\lambda \frac{\dot{E}_{BZ,vis}}{M_B} \left(1 + \frac{\dot{E}_{BZ,D}}{\dot{E}_{BZ,vis}} \right). \quad (6)$$

In the case of a force-free monopole magnetosphere, the energy release by the BZ mechanism is [27, 28]

$$\dot{E}_{BZ,(vis \text{ or } D)} = \frac{1}{6} \left(\frac{\Omega_h \Psi_{(vis \text{ or } D)}}{8\pi} \right)^2. \quad (7)$$

The angular velocity of the black hole is denoted by Ω_h . The magnetic flux threading the black hole is denoted by $\Psi \approx (\text{Area}) B_z$. The field component is given by [44] $B_{z,(vis \text{ or } D)}^2 \approx \left(\frac{H}{R} c_s \right)^2 \rho_{(vis \text{ or } D)}$. We have used H , R , and c_s to denote the accretion disk height, radius, and plasma sound speed respectively and ρ to denote the energy density. We have assumed the sound speed to be approximately equal for the visible sector and the dark sector. This assumption may restrict the microscopic properties of the dark charged plasma to be similar to those of the visible plasma, depending on what specific model is chosen for modeling the accretion disk. Therefore the ratio of released energy is simply

$$\frac{\dot{E}_{BZ,D}}{\dot{E}_{BZ,vis}} = \left(\frac{\Psi_D}{\Psi_{vis}} \right)^2 \approx \frac{\rho_D}{\rho_{vis}}. \quad (8)$$

Substituting (8) into (6) yields our final result for the change in spin Δa measured over some time Δt

$$(\Delta a) \approx -\lambda \left(\frac{\rho_D}{\rho_{vis}} + 1 \right) \left(\frac{\dot{E}_{BZ,vis}}{M_B} \right) (\Delta t). \quad (9)$$

Note that $\rho_{vis} = \frac{384\pi \dot{E}_{BZ,vis}}{(\Omega_h H_{vis} c_{s,vis})^2} \left(\frac{R_{vis}}{r_H} \right)^2$. Obviously, this approach is only feasible if the time between spin measurements is long enough that the $U(1)_D$ sector also has an opportunity to emit a jet and therefore extract some rotational energy from the black hole. In particular, we are assuming that the dark jet and visible jet are emitted at approximately the same time. Deviations from this assumption will become less important if the time between black hole spin measurements is longer. If the dark jet begins emitting before or at the same time as the visible jet, measurements of the visible sector will show a discrepancy. However, if numerical simulations show there may be significant delay in starting the dark jet emission relative to the visible jet emission one must multiply the ratio of densities in (9) by a Heaviside function to account for the delay.

If the measurement is consistent with $\rho_D/\rho_{vis} = 0$, there are several possible explanations. Obviously, it may indicate that there is no such dark $U(1)_D$ sector in nature. Or the mass-to-charge ratio is too large and/or the fine structure constant is too small so that pair production is not efficient [27] and/or the Alfvén speed cannot exceed the local free fall speed at the ergosphere [38]. In addition, the dark sector magnetic

field does not benefit from the existence of the visible progenitor star magnetic field. This could require a more efficient magnetic field generation by the dark accretion disk than is present in the visible accretion disk.

If the microscopic properties of the $U(1)_D$ sector are appropriate for observing an effect, it may indicate that there is not enough energy density of dark matter in the vicinity of the black hole to compete with the energy density of the visible sector. The visible sector has former star remnants in the immediate vicinity to source visible jets. The dark sector requires instead the presence of a dense dark structure such as a dark brown dwarf. Note that solar capture of dark matter in the visible progenitor star will not be significant since we have not allowed interactions between the dense core of the visible star and dark matter, other than gravitational interactions.

A SIMPLE ESTIMATE

In the following we estimate the change in spin value during a GRB for the case where the density ratio is one. Observations have shown that long gamma ray bursts may easily last for $\sim 10^2$ seconds. We will be optimistic and assume spin measurements can be made over the timespan of $(\Delta t) \approx 10^2$ seconds. For simplicity we will assume that throughout the measurement the power emitted is constant. In principle the power emitted will change with time, but this happens at a much slower rate than the spin parameter itself. Therefore if the time between spin measurements do not allow the spin parameter to evolve significantly more than 1%, the variation of power emitted may be neglected for a rough estimate.

For an initial spin of $a \approx 0.9$, we obtain $\lambda \approx 1.6$ and therefore $(\Delta a) \approx -0.03$. This value would only be half as large in the absence of the dark $U(1)_D$ sector jets. To distinguish these two cases experimentally, we must have the precision to measure spin to the second decimal place with enough time resolution to distinguish the beginning and ending spin for a given visible jet event. Other astrophysical jet sources such as supermassive black holes do not yield a significant signal due to the suppressed \dot{E}_{BZ}/M_B relative to gamma ray bursts.

CURRENT AND FUTURE MEASUREMENTS

Recent measurements by NuSTAR, XMM-Newton, and Suzaku [45] of Fe $K\alpha$ spectral emission have allowed astronomers to fit the supermassive black hole spin a , the visible accretion disk radius R_{vis} , the visible accretion disk height H_{vis} , and the visible plasma sound speed $c_{s,vis}$. This method has also been employed for

determining the spin of stellar mass black holes (see [42] for a review and discussion of methods). Since the redshift of supermassive black holes for which spin has been measured is comparable to that at which we observe some gamma ray bursts, it seems to us that it is possible in principle to perform this measurement for the stellar mass black hole that may underlie long gamma ray bursts.

The Astro-H [46, 47] experiment scheduled to launch in 2015 and proposed experiments such as IXO/AXSIO [48], ATHENA+ [49, 50], Extreme Physics Explorer (EPE) [51], and the Large Observatory For Timing (LOFT) [52] would further increase our abilities to measure these parameters to greater precision. Further precision improvements on these values will greatly reduce the uncertainty in our calculation arising from $\mathcal{O}(1)$ factors.

In the previous section we showed that in order to detect the dark $U(1)_D$ sector one must be able to measure a 1% change in the spin parameter with a time resolution capable of distinguishing the beginning and end of a long gamma ray burst. To our knowledge, no attempt has been made to measure the spin of a stellar black hole during the gamma ray burst period. We do not know whether current techniques and experiments used for measuring black hole spin are capable of doing so or not. The purpose of this letter is to make the case that such measurements should be considered and would have profound implications.

Currently the only evidence we have that dark matter exists is through gravitational effects, therefore it may be that dark matter only couples gravitationally to visible matter. A discrepancy between how quickly a black hole decreases its spin and how much energy has been emitted in visible jets could provide positive evidence that there exists a dark unbroken $U(1)_D$ sector in the universe, which is capable of emitting jets of dark radiation.

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